Seismic Verification of Nuclear Plant Equipment Anchorage

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1. INTRODUCTION

More than 60 % of the electrical power of Belgium is generated by 7 PWR nuclear plants. For 3 of them, electro-mechanical equipment had to be reassessed after ten years of operation because the seismic requirements were upgraded from 0.1 g to 0.17 g free field ground acceleration.

Seismic requalification of the active equipment was a critical problem as the classical methods were too conservative and their application would have lead to unacceptable replacement or reinforcement of a lot of equipment.

The approach based on the use of past experience of seismic behavior of non nuclear equipment, chosen and developed by the SQUG (a group of U.S. utilities), had to be transposed to the Belgian N.P.P.

Engineers, members of a SRT (Seismic Review Team), applying the database experience decide upon the acceptability of the equipment during a walkdown of the plant. The decision relies heavily on the seismic capacity of anchorage configurations. To support the SRT work in this area, the Electrical Power Research Institute (EPRI) developed procedures and guidelines for the demonstration of the seismic adequacy of equipment anchorages in a cost-effective and consistent manner.

The document (Ref. 1) prepared by EPRI could not be used, as it related only to U.S. anchor bolts and U.S. practice. As a consequence, the EPRI report had to be adapted to the specific Belgian situation especially for the type of fasteners, the manufacturers of expansion bolts, the strength criterion developed for each of the fastener types and the methodology used to identify the different types during walkdowns.

The general approach for equipment anchorage verification is to combine a field inspection with an office work performed after walkdown.

2. FIELD INSPECTION PROCEDURE

The goal of the field inspection procedure is to identify the type of fastener and to detect their possible installation defects. By implementing this inspection, a detailed drawing of the anchorage configuration is established. The following information is noted : type of fastener, steel yield strength (f_y), concrete compressive strength (f'_c), bolt diameter (D), free-edge distance (E), bolt spacing (A), embedment length (P) and concrete thickness (H).

2.1. Type of fastener

Due to the fact that the distinctive elements of anchorages are embedded in the concrete, this identification is certainly one of the most difficult tasks to be performed by the SRT members during the walkdown. Therefore the information given by the contractor files to identify the type of fastener as well as its embedment length and its mechanical characteristics is a priori considered and, if possible, verified. However, in case of incomplete or unavailable written information, the SRT members identify :

1. the type of fastener on the basis of the following topological considerations :
   a. a throughwall bolt is characterized by an anchor head plate,
   b. the threaded rod or bolt diameter of an expansion anchor bolt is equal to or less than 20 mm,
   c. a pedestal and a threaded rod diameter greater than 20 mm characterize cast-in-place or J-bolts,
   d. the self-drilling type or drop-in-type shell expansion anchor bolts have internal threads for inserting a bolt.
2. the embedment length P for the identified type of fastener from the following rule :
   a. P = concrete thickness (H) for a throughwall bolt,
   b. P = half height of the formed hole for the embedded anchors,
   c. P = minimum embedment length given by the manufacturer for the expansion anchor bolts.
3. the steel mechanical characteristics by reading the steel grade stamped or by taking 235 MPa as minimum value for the yield strength f_y.

2.2. Installation defects

The following nine steps constitute a simple procedure that can be applied to all types of bolts to detect poorly installed ones. For maximum assurance of adequacy, all nine of those steps must be performed for all bolts. However, for identical equipment, supplied and installed by the same contractor, adequate assurance adequacy can be achieved by a less extensive program. Only 25 % of the bolts are fully inspected, the balance being only visually inspected. If the selected bolts do not pass the inspection, then all steps must be performed on all bolts in the anchorage configuration.

1. <u>Are the nut and anchor bolt tight</u> ? This step will detect oversized holes, loose nuts, damaged subsurface concrete and missing plug. To implement it, a torque M_a is applied by means of a wrench placed on the bolt head or nut.

   $$M_a\ (Nm) = 0.01\ D^3 \text{ with } D \text{ in mm}$$

   A well-installed bolt should not rotate under the torque applied. A small amount of initial rotation is acceptable provided the nut or bolt will tighten and resist the applied torque.
2. <u>Do washers exist between the equipment base and the anchor bolt nut or bolt head</u> ? Washers are required for all bolts and lock washers are mandatory for pumps and motors anchorages.
3. <u>Is the bolt spacing A greater than the minimum value A_{min} given in table 1</u> ? This step will detect improper expansion anchor bolt spacing. If the bolt spacing A is less than A_{min}, one of the two bolts is ignored.
4. <u>Is the distance E between the expansion anchor bolt and any free concrete surface greater than the minimum value E_{min} given in table 1</u> ? This step will detect improper edge distance and if the edge distance E is less than E_{min}, the bolt is ignored.

5. Is the concrete sound and uncracked ? This step will detect gross defects as a broken pedestal edge, a lack of concrete, ... Cracks less than 0.5 mm are no matter of concern. Anchorages in masonry are not allowed.
6. Is there a gap greater than 5 mm between the equipment base and the concrete surface ? In case of positive answer, the anchorage must be evaluated in detail.
7. Is the thickness of the concrete equal to or greater than the minimum value H_{min} given in table 1 (for expansion anchor bolts only) ? This step will identify insufficient thickness of concrete to obtain the minimum embedment length specified by the expansion anchor bolt manufacturer.
8. Is the anchorage degraded by corrosion or mechanical abrasion ? In case of positive answer, the anchorage must be ignored for seismic resistance.
9. Is the equipment anchorage configuration subject to base flexibility and prying action ? The common characteristic of those two separate phenomena is that they can lead to anchorage failure at load levels less than the loads needed to cause fastener failure. To identify that defect, the SRT members will pay attention to anchorage configuration showing a disproportion between the bolt diameter and the thickness of the base plate just as anchorages far from the side wall in case of electrical cabinets. Implementation of this step requires the verification of the following criteria :

   a. $e \geq 0.8\ D$ where $e =$ thickness of the base plate
   $D =$ bolt diameter

   b. $x \leq 5$ cm where $x =$ distance between the wall of the electrical cabinet and the bolt axis.

   In case the above criteria are not met, the anchorage configuration must be evaluated in detail without taking into account the strength criteria given in paragraph 3.

3. OFFICE WORK

This section presents the verification procedure developed to calculate the seismic capacity of equipment anchorages. It consists of the 3 following steps :

1. Calculate strength of fasteners,
2. Calculate the seismic anchorage capacity,
3. Compare the seismic anchorage capacity to the demand.

Only the first step is particular to the Belgian plants and will be developed in this paper. The two others can be solved by using well-known computer programs as JABSAE (Ref. 1) or ANCHOR (Ref. 2) to perform interactive analysis of equipment anchorage under base excitation loadings. Given the anchorage geometry, the strength of fasteners, the dead load and a seismic external load, the programs calculate a minimum allowable load factor. This load factor is the ratio of the allowable seismic load magnitude (capacity) over the applied seismic magnitude (demand). A load factor of less than 1.0 would indicate an equipment with insufficient anchorage strength.

3.1. Strength of fasteners

The types of fasteners addressed consist of throughwall bolts, cast-in-place including J-bolts, dovetailed anchors, steel sheets and hammer head rods, rails and expansion anchor bolts. A strength criterion combining the tension and shear limitations with shear-tension interactive equation (Fig. 1) is developed for each type using both manufacturers data and test results for the expansion anchor bolts and the ACI (Ref. 3) design guidelines for the other types of fasteners completed by pullout test results for the cast-in-place anchors. It must be noted that the strength of fasteners is calculated with the "as-built" data coming from the field inspection performed before the office work. The following strength criteria were developed :

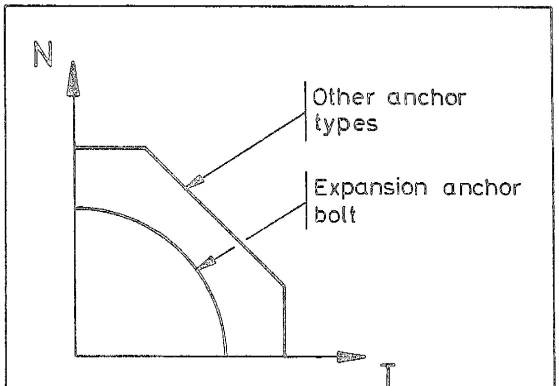

Figure 1

Throughwall bolt

The strength criterion is determined by application of the principle set forth in ACI-349 (Ref. 3).The parameters used hereafter are defined in the ACI Code. Two types of failure mechanisms are considered : anchor tensile failure and concrete cone failure.

Tension capacity :

$$N = min\left(\emptyset_N\ \Omega_n\ f_y,\ 0.33\ \emptyset_c\ S_e\ \sqrt{f'_C}\right)$$

Shear capacity :

$$T = min\left(\emptyset_N\ \Omega_n\ f_y,\ 0.33\ \emptyset_c\ S_e\ \sqrt{f'_C}\right)$$

Shear-tension interaction :

$$1.\ \frac{N}{\emptyset_n} + \frac{T}{\emptyset_T\ \mu} < \Omega_n\ f_y$$

$$2.\ N < 0.33\ \emptyset_c\ S_e\ \sqrt{f'_C}$$

$$3.\ T < 0.44\ E^2\ \sqrt{f'_C}$$

Cast-in-place including J-bolt - dovetailed anchor

For these types of anchors, a third mechanism of failure must be added : the anchor slip failure. Complementary limitations to those for throughwall bolt have been introduced to calculate the tension and shear capacities to avoid slip failures (Ref. 4).

$$N < \emptyset_n\ 0.05\ f'_c\ \pi\ D\ P$$

$$T < \emptyset_T\ \mu\ 0.05\ f'_c\ \pi\ D\ P$$

Steel sheets and hammer head rods

The strength criterion is determined from the formula given for the throughwall bolt and by limiting the tension capacity to $0.595\ \emptyset_d\ f'_c\ \sqrt{A_2\ A_1}$ (Ref. 3) to consider the crushing of the concrete which can produce a loss of stiffness of anchorage.

Expansion anchor bolts

Four types of expansion anchor bolts (self-drilling type shell anchor, drop-in type shell anchor, sleeve-type anchor and wedge-type anchor) with sizes ranging from M6 to M20 were selected after review. They represent five manufacturers and the types and sizes mostly used in the plants under consideration.

The strength criterion (Fig. 1) to judge the acceptability of an expansion anchor bolt is obtained through a quadratic shear-tension interaction equation based on the hypothesis that tension *(N)* equals shear *(T)*.

The tension capacity *(N)* is calculated by applying a safety factor of 4 on the mean ultimate tension loads X_m given in the manufacturer's catalogs or obtained from a testing program (Ref. 5) and modified by three coefficients to take into account the effects of the concrete cracking (f_f), the loading mode (f_d) and the concrete aging (f_v)

$$N = \frac{X_m}{4} f_f \, f_d \, f_v$$

In this approach the embedment length P is assumed to be the minimum required by the manufacturer so that the protection against the slip failure is taken into account in the determination of the ultimate tensile load X. f_f and f_d derive from a statistical analysis of the results of a large static and dynamic testing programme (Ref. 5).

$f_f = 0.87$: reduction coefficient of X_m for bolts located in cracked concrete with crack opening equal to 0.3 mm.

$f_d = 0.90$: reduction coefficient of X_m for service level D, cracked concrete and dynamic loading.

f_v derives from manufacturer's test data on bolts installed in concrete slabs of different strength and from a ratio of 1.46 (Ref. 6) between the actual strength and the design strength for an aging of at least 3 years. This leads to 1.15 as typical value of f_v.

Typical values of tension capacities for all identified types of bolts are presented in table 2. These values are given for a strength of concrete f'_c of 25.5 MPa and for a specific anchorage configuration defined by the bolt spacing A, the free-edge distance E and the concrete thickness H to avoid the concrete cone failure mechanism.

However, in order to have a specific bolt strength criterion, the effect of strength of concrete and anchorage configuration are factored out below :

a. Strength of concrete f'_c : the ultimate tension load of expansion anchor increases with the strength of concrete f'_c. To quantify this phenomenon, a manufacturer gives the following correction factor f_b to apply to N :

$$f_b = 1 + \frac{0.020}{0.85} (f'_c - 25.5) \text{ with } f'_c \text{ in MPa}$$

b. Bolt spacing A and free-edge distance E : for a group of two or more bolts, all of which have less than the required spacing A and/or free-edge distance E specified in table 2, one or two reduction factors that reduce the tension capacity N must be applied : f_A for an insufficient bolt spacing and f_E for an insufficient free-edge distance. These factors depend on the type of bolt :

1. Self-drilling type shell anchor :

$$f_A = 0.94 \frac{A_r}{A} + 0.06 \text{ for } 0.57 \leq \frac{A_r}{A} \leq 1$$

E given in table 2 must always be met.

2. Drop-in type shell anchor :

$$f_A = 1.16 \frac{A_r}{A} - 0.16 \text{ for } 0.57 \leq \frac{A_r}{A} \leq 1$$

E given in table 2 must always be met.

3. Sleeve and wedge type anchor :

$$f_A = 0.25 + 0.75 \frac{A_r}{A} \text{ for } 0.3 \leq \frac{A_r}{A} \leq 1$$

$$f_E = \frac{E_r}{E} \qquad \text{for } 0.6 \leq \frac{E_r}{E} \leq 1$$

c. Concrete thickness H : the value given in table 2 must always be met.

In presence of a non-identified bolt, the SRT members consider the minimum values of N, A, E and H for the size found.

Rails

Rails are fairly common for electrical cabinets. To assure adequate anchorage, it is necessary to verify the attachment of the equipment to the rail and of the rail to the concrete floor. Only the latter is covered by the strength criteria described above.

4. CONCLUSION

Although the anchorage verification procedure developed in this paper does not use screening tables that give the seismic capacity of common anchorage systems, it presents the following advantages :

1. the field work is minimized and recorded.
2. the office work may be performed a long time after the walkdown.
3. the verification corresponds exactly to the anchorage verification, so that an outlier is directly detected.

REFERENCES

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Bolt dia.	Self-drilling type anchor			Drop-in type anchor			Sleeve-type anchor			Wedge-type anchor		
	A_{min} (cm)	E_{min} (cm)	H_{min} (cm)	A_{min} (cm)	E_{min} (cm)	H_{min} (cm)	A_{min} (cm)	E_{min} (cm)	H_{min} (cm)	A_{min} (cm)	E_{min} (cm)	H_{min} (cm)
M6	-	-	-	5.0	7.5	10.0	-	-	-	3.0	3.0	10.0
M8	-	-	-	6.0	9.0	10.0	6.0	6.0	15.0	4.0	4.0	10.0
M10	-	-	-	8.0	12.0	12.0	8.0	8.0	18.0	4.0	4.0	12.0
M12	11.0	16.0	16.0	10.0	15.0	16.0	9.0	9.0	20.0	6.0	6.0	16.0
M16	13.0	19.0	20.0	13.0	19.5	20.0	13.0	13.0	22.0	11.0	11.0	20.0
M20	17.0	25.0	25.0	16.0	24.0	25.0	14.0	14.0	26.0	13.0	13.0	25.0

Table 1

Bolt dia.	Self-drilling type anchor				Drop-in type anchor				Sleeve-type anchor				Wedge-type anchor			
	N (kN)	E (cm)	A (cm)	H (cm)	N (kN)	E (cm)	A (cm)	H (cm)	N (kN)	E (cm)	A cm)	H (cm)	N (kN)	E (cm)	A (cm)	H (cm)
M6	-	-	-	-	1.0	7.5	9.0	10.0	-	-	-	-	2.5	5.5	11.0	10.0
M8	-	-	-	-	1.7	9.0	10.5	10.0	4.1	10.5	21.0	15.0	3.9	6.0	12.0	10.0
M10	-	-	-	-	4.3	12.0	14.0	12.0	6.8	12.5	25.0	18.0	4.6	7.0	14.0	12.0
M12	4.6	16.0	18.5	16.0	7.4	15.0	17.5	16.0	10.1	15.0	30.0	20.0	8.2	9.5	19.0	16.0
M16	7.5	19.0	22.0	20.0	10.0	19.5	23.0	20.0	13.6	20.5	41.0	22.0	11.7	17.5	35.0	20.0
M20	12.4	25.0	29.0	25.0	16.4	24.0	28.0	25.0	20.2	23.5	47.0	26.0	16.6	21.0	42.0	25.0

Table 2